Applications of Digital Storage Receivers for Enhanced Signal Processing

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BIOGRAPHY

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Alison Brown is the President and CEO of NAVSYS Corp. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge Univ. In 1986 she founded NAVSYS. Currently she is a member of the GPS-III Independent Review Team for the USAF and serves on the GPS World editorial advisory board.

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ABSTRACT

This paper describes the architecture of a digital storage receiver and discusses its benefits and applications. The digital storage receiver includes the capability to record the raw GPS data which can then be "recirculated" in non real-time through the receiver processing functions. An analysis is included to demonstrate the advantage of this technique in performing direct P(Y) code search and acquisition and tracking GPS in a jamming environment.

1 INTRODUCTION

In this paper the advantages of the digital storage receiver are described for a variety of different applications. Since the GPS signals do not have to be processed in real-time, enhanced signal processing algorithms can be applied that allow the digital signals to be optimally reprocessed, maximizing the probability of acquiring the GPS signals in a challenging environment.

In the Digital Storage Receiver (DSR) architecture illustrated in Figure 1, the RF Digital Front-End (DFE) includes the antenna, filters, amplifiers and down-converters needed to digitally sample the GPS signal spectrum. Depending on the application (see section 5), this signal is either digitally recorded using a data logger co-located with the DFE or connected through a telemetry link.

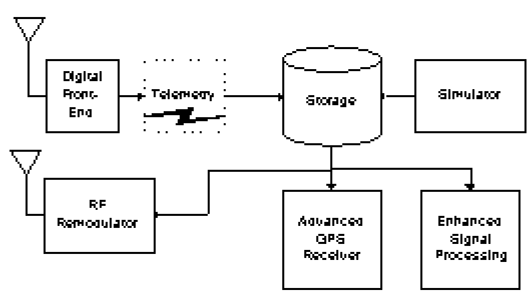

Figure 1 Digital Storage Receiver Architecture

The stored digital GPS data is then played back either into a digital GPS receiver, such as NAVSYS Advanced GPS Receiver (AGR)[1], or into a signal processor module where digital signal processing software is used to acquire

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and track the GPS signals. As an option, the recorded digital signals can also be remodulated onto an RF carrier to be played back into a receiver antenna input. The capability also exists to generate simulated digital data files for playback in the digital storage receiver architecture.

2 DIGITAL STORAGE RECEIVER PRODUCT FAMILY

In Table 1, the family of GPS data storage products that NAVSYS have developed is summarized.

Table 1 NAVSYS Digital Storage Receiver (DSR) Product Line

Model	DSR 100	DSR 110	DSR 200
DFE input	1-bit	1-bit	1-12 bits
Data sample	I only	I,-Q,-I,Q	I,-Q,-I,Q
Data Rate	2-8 Msps	2-40 Msps	2-40 Msps
Frequency	L1	L1	L1/L2
Storage	2-30 Gbyte	32 Mbytes	8 Gbytes/card
Form Factor	Desktop PC	Desktop PC	Compact PCI

2.1 DSR-100

The DSR-100 was the first PC-based DSR product introduced by NAVSYS. This product consists of two ISA personal computer (PC) boards as shown in Figure 2. The first board includes the GPS DFE which uses a commercial chip set to mix the GPS signals to a 308.88888 kHz IF band-limited to 5MHz for 1-bit sampling. The second data logger board streams the GPS data to the PC hard-drive where it is recorded. The DSR-100 has both record and playback modes. The DSR-100 can support data logging at up to 8 MHz sample rates. The capacity of the DSR is a function of the size of the hard drive installed in the PC. With a 2 Gbyte hard-drive over 2 hours of 2 Msps data can be stored.

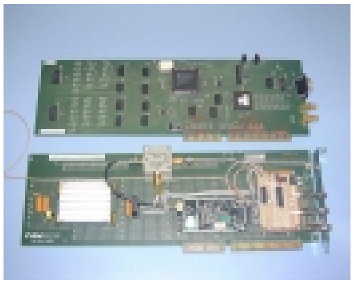

Figure 2 DSR-100

2.2 DSR-110

The DSR-110 was designed by NAVSYS to allow the full GPS bandwidth to be captured for analysis. This product consists of a DFE module and two ISA PC boards as shown in Figure 3. The DFE module includes the circuitry to downconvert the GPS signals to a 69.92 MHz If bandlimited to 20 MHz and provide a 1-bit sampled output for data logging at a peak sample rate of 40 Msps. Since the sample rate is at approximately 1.75 cycles of the IF, this has the same effect as I and Q sampling with the data following the sequence I,-Q,-I,Q. Which can then be ordered for post processing. The DFE module provides the data through an interface card to a PC board which includes 32 Mbytes of memory storage. This allows a burst of up to 6.4 seconds of broad-band GPS data to be collected for analysis.

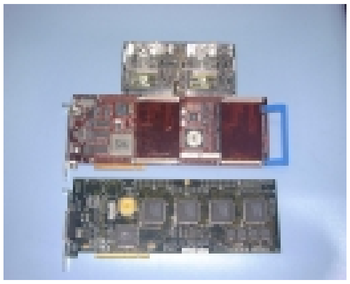

Figure 3 DSR 110

2.3 DSR-200

NAVSYS' latest generation DSR product has the capability of storing the complete GPS spectrum (20 MHz) with up to 12 bit resolution on both the L1 and L2 signals. When operated in conjunction with our GPS Precise Positioning Service (PPS) enhanced digital signal processing (DSP) card, this system provides the capability for performing direct P(Y) code acquisition on the GPS signals and enables implementation of enhanced tracking algorithms in a jamming environment. The DSR-200 is designed using the ruggedized Compact PCI form factor and includes the following boards: a DFE that provides 12-bit sampled GPS data at a 69.92 MHz IF (L1) or a 70 MHz IF (L2) band-limited to 20 MHz; a PPS DSP board for post-test analysis; and one or more data storage cards that each include 8 Gbytes of memory storage. The storage can be configured from 1 to 12 bit wide L1 or L2 data depending on the application. Each memory board for example could be used to record up to 204.8 seconds of 8-bit L1 or L2 I,-Q,-I,Q sequenced 40 Msps input data, or 136.5 seconds of 12-bit L1 or L2 40 Msps data.

3 GPS SIGNAL PROCESSING

The performance advantage of a digital storage receiver when operating in an electronically challenged environment is discussed in this section.

3.1 DIRECT P(Y) CODE ACQUISITION

The problem of acquiring a long pseudo-noise code has conventionally been handled in the case of GPS by first acquiring a shorter code, C/A, which, in conjunction with the data message, enables time synchronization for subsequent acquisition of the P(Y) code. The disadvantage of first acquiring the C/A is that it is an unencrypted code and can be more easily spoofed. The classical difficulty with the long code is that the search process, which must be performed in the two dimensions of code phase and carrier frequency, takes too long under

most practical signal to noise ratios. The P(Y) code has a very low repetition-rate-to-bandwidth ratio and, as a result, synchronization of a receiver to a specified modulation constitutes a major difficulty.

Considerable research and effort are now being expended to reduce the acquisition time by either: 1) aiding the receiver with extremely accurate time and frequency 2) increasing the hardware resources in the receiver, usually accomplished with a massively parallel correlator design, which increases the number of independent correlators. As will be seen, the GPS digital storage receiver concept is a complementary technique to enable direct P(Y) acquisitions with a reduced amount of signal exposure time.

The process of aligning the P(Y) code, which is biphase modulated, to within half a code chip, is referred to as acquisition. The local PN-code generator is set at some initial code epoch and the carrier Numerical Controlled Oscillator (NCO) is set at some initial carrier frequency. This replicated signal is cross correlated with the received signal plus noise, coherently integrated over a Predetection integration time denoted as T_c, thereby generating the in-phase and quadrature samples $I(kT_c)$ and $Q(kT_c)$, respectively. As shown in Equation 2, these are then square-law detected, and, if necessary, summed with other samples. The sum of the samples is then compared to a detection threshold, the magnitude of which is dependent on the allowable probabilities of false alarm and successful detection. In Equation 3 and Equation 4 the algorithms for computing the probability of missed detector and false alarm are shown for a specified signal-to-noise threshold (CN_T). These are derived in terms of the chi-square function $P(\gamma|2N_{NC})$ and the non-central chi square function $P(\gamma|2N_{NC},\lambda)$.

Equation 1

$$I_k = \int_{(k-1)T_c}^{kT_c} I(t)dt \quad Q_k = \int_{(k-1)T_c}^{kT_c} Q(t)dt$$

Equation 2

$$z = \sum_{k=1}^{N_{NC}} I_k^2 + Q_k^2$$

Equation 3

$$\begin{aligned} P_{FA} &= \Pr ob(z \geq \gamma\sigma_n^2 \mid CN_0 = 0) \\ &= Q(\gamma \mid 2N_{NC}) = 1 - P(\gamma \mid 2N_{NC}) \end{aligned}$$

Equation 4

$$\begin{aligned} P_{MD} &= \Pr ob(z < \gamma\sigma_n^2 \mid CN_0 = CN_T) \\ &= P(\gamma \mid 2N_{NC}, N_{NC} \times CN_T) \end{aligned}$$

The process of integration over T_c is known as the predetection integration interval. In general, to reduce the effects of noise on the operation of the detection process, it is desirable to make T_c as large as possible, before having to resort to summing over N_{NC} noncoherent samples (I^2+ Q^2). However, the length of T_c is limited by the frequency uncertainty, which in turn is due to oscillator instabilities and unknown doppler effect.

Each search must be performed for every possible code-phase/doppler frequency bin. The uncertainty in code phase is due to user clock uncertainties plus user to satellite range uncertainty. For example, a user clock uncertainty of one millisecond (random zero mean Gaussian bias - one standard deviation) and an additive user to satellite range uncertainty of 30,000 meters (random independent Gaussian bias - one standard deviation) would result in a 3-sigma (99%) search region of 10279 x 2 x 2 x 3≅123,345 bins. The doppler bin size is dictated by the coherent integration period. To maintain the correlation loss due to doppler uncertainty within 3 dB, the size of each frequency window should be kept within $0.442/T_c$. If the Doppler one sigma uncertainty and the receiver oscillator uncertainty is within 1 kilohertz, and the coherent integration period (T_c) was set at 20 milliseconds (the GPS data bit period), then the number of discrete frequencies to search over would be approximately 384.

In this scenario, the total number of bins that would need to be searched to assure P(Y) code acquisition would be over 47 million (123,345x384). It is this large number of bins to search which creates, in many operational scenarios, the impracticality of Direct Y acquisition in an acceptable time.

With a conventional GPS receiver, the present approaches to reducing the acquisition time are:

- Time aiding the receiver with external clocks typically better than 1 millisecond. This reduces the number of searches by reducing the code phase uncertainty.
- Massively parallel correlators. This enables the simultaneous or parallel processing of many bins at once.
- Improving the signal-to-noise ratio at the input to the receiver. As will be shown subsequently, the acquisition time varies directly with the product of the coherent integration interval, T_C and the number of summations, N_{NC}. This product is sometimes referred to as the dwell time per bin for a single search frequency.

In conventional GPS receivers, the acquisition process must occur in real time implying that the signal must be always available in real time. This furthermore means that the antenna must be exposed during the lengthy long code acquisition process.

The storage receiver provides an alternate strategy. By storing the broadband signal, the signal can be "recirculated" in non real-time among the correlator resources. Instead of having to slew the correlator resources in real time to the incoming signal until

synchronization is achieved, the storage receiver can "recirculate" the wideband signal in post time without requiring further signal collection. Thus the storage receiver would reduce antenna exposure time for those platforms which desire to remain stealthy. Since, at least theoretically, the signal can be "recirculated" forever, the storage concept guarantees an "eventual" acquisition within the given exposure time. Theoretically, for very short data collection intervals, one would have to be concerned with the uniqueness of the sample of the code pattern; however, for practical purposes, data collection intervals less than one second are not required and therefore the uniqueness of a pattern 10^7 bits or longer is not an issue.

3.2 PROBABILITIES OF DETECTION

The probability of false alarm (P_{FA}) can be computed as shown in Equation 3. The probability of detection (P_D) can be computed from the probability of missed detection shown in Equation 4 (P_D=1-P_{MD}). These probabilities are derived using non-central chi-square density statistics as a function of the following parameters.

- N_{NC} the number of non-coherent accumulations in the detection function
- CN_T the signal-to-noise ratio threshold
- σ_n the RMS noise in the I or Q accumulated samples
- γ the threshold value for detection to be declared.

Several references [2,3,4,5] have addressed closed form and or mathematical approximations to solving the above integrals and parametrically determining acquisition design parameters. Chi-square density functions are intricate analytic functions and are not amenable to simple manipulation, although numerical tabulation of their integrals is readily available.

In the above distributions, once probabilities of false alarm and detection are chosen according to the mission requirements, then the threshold (γ) and number of coherent integrations (N_{NC}) may be solved for in terms of the noise power, signal power, and predetection interval. Equation 5 is an approximation which provides the number of coherent integrations necessary to achieve a given P_{FA} and P_D as a function of γ [2].

Equation 5

$$N_{NC} \cong \frac{\pi}{2}\left[\frac{\sqrt{\log_e\left(\frac{1}{4P_{FA}}\right)}+\sqrt{\log_e\left(\frac{1}{4P_D(1-P_D)}\right)}\sqrt{1+2\gamma}}{\gamma}\right]$$

Figure 4 utilizes modifications of this equation to plot dwell time per bin, $N_{NC}T_C$, versus C/N=γT_C for a P_D of 0.95 and a P_{FA} =10^{-4}.
Figure 5 to Figure 7 also utilize Equation 5 to inversely solve for the P_D as a function of C/N with dwell time per bin, $N_{NC}T_C$, and T_C as parameters. The reason for choosing dwell time per bin as a parameter will become apparent in the next section where we discuss search times.

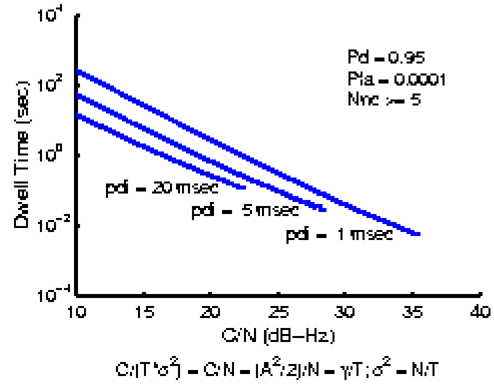

Figure 4 Dwell Time as a Function of C/N

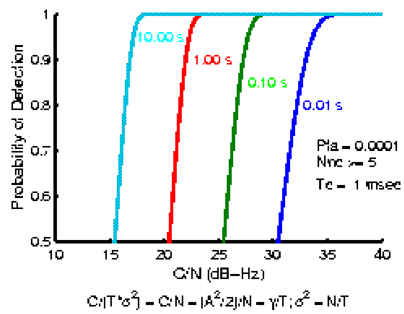

Figure 5 Probability of Detection at Various Dwell Times

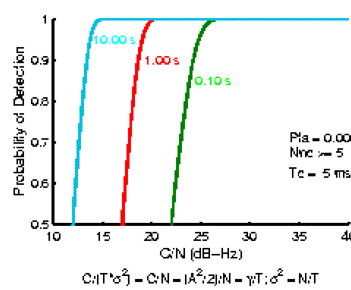

Figure 6 Probability of Detection at Various Dwell Times

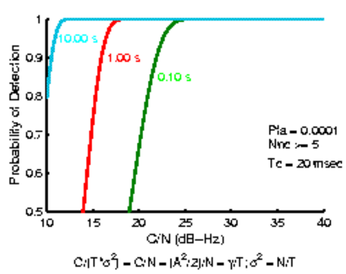

Figure 7 Probability of Detection at Various Dwell Times

3.3 RECEIVER TIMING DEFINITIONS

The search time for a conventional receiver is defined as the time required to search and acquire the GPS satellite signals. It should be distinguished from time to first fix for a GPS receiver which would normally include factors such as acquisition and declaration of track for several satellites, bit synchronization, and Kalman filter fix convergence. It should also be distinguished from exposure time, which is the time that the satellites must be in view of the antenna for a fix to be obtained. In the case of a conventional GPS receiver, the exposure time must be equal to or greater than the time-to-first-fix, while, for the case of the storage receiver, exposure time represents the signal collection interval. The processing time is the time required for the receiver to compute a navigation solution following the exposure time. In the case of the storage receiver, the processing time is a function of the speed and capacity of the storage receiver's signal processing board. NAVSYS have developed a high speed signal processing design that enables highly efficient direct P(Y) code acquisition performance. This processing speed will be the subject of a later paper to be published.

For many of the applications described in section 5, minimizing exposure time is critical either due to covert operations requirements or due to the dynamically changing nature of the environment around the GPS receiver. In the following section, a comparison is made of the needed exposure time between a conventional and a digital storage receiver.

A simple expression for the average sequential or serial search time in a conventional receiver is: $T_{\text{search}} = 1/2 N_{BINS} N_{NC} T_C$

The average, or expected value of the random variable, search time, is therefore ½ of the product of the number of bins to search and the dwell time per bin. Here the factor ½ occurs because that, on average, one will not have to search all the bins, but only until a detection occurs. This expression is somewhat simplistic because it does not account for the occurrence of false alarms and the subsequent time penalty which they cause. A more complete formula for the mean serial search time is given in Equation 6 below:

Equation 6

$$T_{search} = \left(\frac{2-P_D}{2P_D}\right)\left[k_p P_{FA} + 1\right] N_{BINS} N_{NC} T_C$$

In the numerical examples in this paper we chose k_p=10, $P_{FA}=10^{-4}$, and P_D=0.95. shows the normalized mean acquisition search time as a function of the C/N for different predetection integration times.

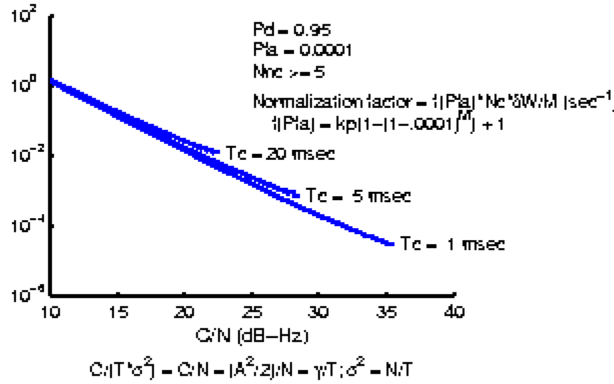

Figure 8 Search time for conventional receiver

A conventional receiver uses multiple correlators to reduce the search time. For M correlators operating in parallel simultaneously the simple result would indicate that the average search time would be reduced by a factor of M.

$$T_{\text{search}} \cong 1/2 N_{BINS} N_{NC} T_C \,/\, \text{M}$$

A more precise formula, which assumes that each of the M blocks are independent and that no additional penalty occurs when multiple false alarms occurs is given as:

Equation 7

$$T_{\text{SEARCH}} = \left(\frac{2-P_D}{P_D}\right)\left\{\left[k_P\left(1-\left(1-P_{FA}\right)^M\right]+1\right\} N_{BINS} N_{NC} T_C \,/\, \text{M}$$

Note that in Equation 7, the number of bins depends on the frequency window size, which depends also on T_C. Therefore normalization by determining a mean search time per bin is not a useful methodology except for the case where there is only one frequency to search over. plots the normalized search time versus C/N.

The exposure time for a storage receiver is derived from the probability of correct detection in a single search bin.

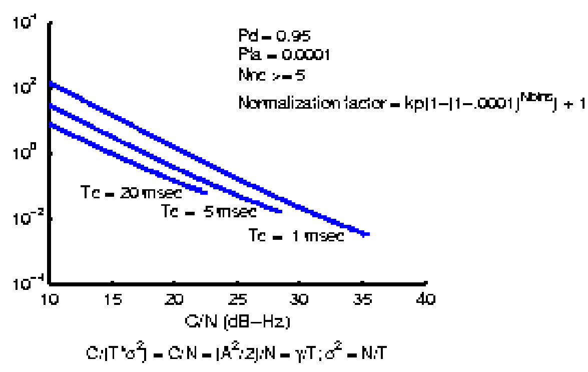

Figure 9 Exposure time for digital storage receiver

Figure 9 plots the exposure time versus C/N for the storage receiver.

4 JAMMER PERFORMANCE

The performance of a conventional and storage receiver in a jamming environment was compared based on the capability of the digital storage receiver to implement optimized enhanced signal processing algorithms to respond to a jammer threat.

The jammer has the effect of adding additive noise to the GPS signal proportional to the jammer/signal (J/S) power ratio[6]. To operate in the presence of a jammer, the receiver must be able to acquire under very low equivalent signal-to-noise ratios. The equivalent signal/noise ratio can be computed from the effective noise that is added by the jammer signal as shown in the following equation.

Equation 8

$$J_{eq} = N_0 R_C + \frac{J}{Q_C}$$

$$N = J_{eq} / R_C$$

In Equation 8, N_0 is the thermal density, J is the jammer noise power, R_C is the P(Y) code chipping rate or equivalently the single sided front end bandwidth, and Q is a factor =1 for a narrow band jammer, 1.5 for a broad band spread spectrum jammer, and 2 for a wide band jammer. For most cases investigating jamming, the jamming power in Equation 8 dominates. In this report, we only used narrow band jammers so the input jammer power is not spread outside of the front end bandwidth.

The following results were generated based on the assumptions shown below. Unless otherwise stated, the values shown are 3-sigma.

- Probability of detection of 0.95 and a probability of false alarm of 0.0001.
- Time/frequency uncertainty of 1 second/10 kHz (basic clock) and time uncertainty of 100 microseconds/2 kHz (atomic clock)
- Sampling and processing implementation loss of 4.1 dB
- Number of correlators available was 50 (Miniature Airborne GPS Receiver) or 1000 (E-MAGR)

For the sake of comparison, the detection algorithms were assumed to use the same core signal processing algorithms, as described in section 3. Under contract to SPAWAR, enhanced adaptive acquisition algorithms are being developed that further leverage the capability of the digital storage receiver architecture. These algorithms will be the topic of a later paper.

4.1 EXPOSURE TIME COMPARISON

Figure 10, represents the mean acquisition time for the conventional receivers and the exposure time for the storage receiver for the case of the Standard Clock.

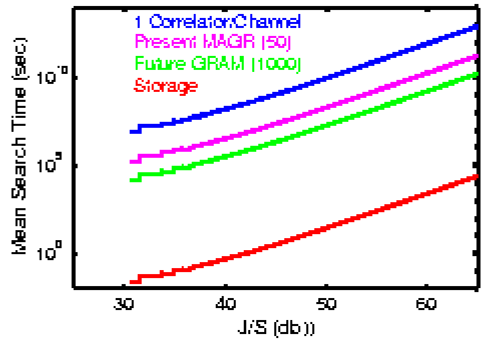

Figure 10 Theoretical Direct Y Search Time to First SV using Standard Clock

For the conventional receivers, the mean acquisition time is defined as the mean time until a successful detection is made. As always herein, acquisition refers only to the code correlation of the first satellite.

Note for the standard quality clock, for any J/S > 30 dB, the conventional receiver mean acquisition times are greater than 10000 seconds, which makes them totally impractical. Even for the 1000 correlator receivers, time aiding to better than 1 second will certainly be necessary to achieve any practical acquisition performance. For the storage receiver, a significantly shorter exposure time is required. However, there will be a delay from the time that the RF snapshot is collected until the time that the navigation solution is available, due to processing time. As discussed in the following section, for stealthy combatants with inertial navigators, it is likely that exposure time is more important than the actual time that a fix is reported. As can be seen from Figure 10, it is possible, even with a standard clock, to achieve fixes in under 100 seconds exposure time at J/S levels of up to 50 dB.

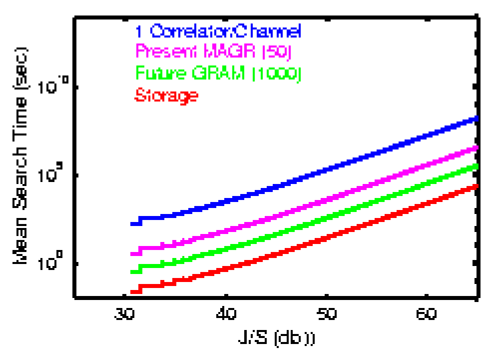

Figure 11 Theoretical Direct Y Search Time to First SV using Superior Clock

Figure 11 shows the mean acquisition/exposure times for the time aided receiver. The aiding quality of 100 μsecs.

(3σ) is indicative of a 1 part in 10^{11} oscillator that has been reset (perfectly)within the last 38 days. For this high quality time aiding, all the receivers except for the 1-correlator receiver could theoretically acquire in 100 seconds up to 41 dB J/S. The relative advantage of the storage receiver, at least with respect to exposure time, amounts to about a 13 dB improvement over the MAGR and 7 dB over the 1000 correlator receiver.

4.2 PROBABILITY OF ACQUISITION COMPARISON

In this section, for a given exposure time we determine the probability that a successful acquisition occurs. The curves for probability of acquisition, were developed using the following assumptions.

- At each bin we spend $N_{NC}T_C + k_P P_{FA} N_{NC} T_C$ seconds.
- By definition the probability of a successful acquisition at a bin where the signal resides is P_D. For a given fixed T_{Search} we may have time to search all the bins once, or only a fraction of the bins (f)

$$f = \frac{\dfrac{T_{SEARCH}}{N_{NC}T_C + K_P P_{FA} N_{NC} T_C}}{N_{BINS}/M_C}$$

From Figure 12 for the standard clock, we note that only the storage receiver, achieves a probability of acquisition greater than 0.5 if restricted to less than 100 seconds. The storage receiver can achieve a 95% probability of acquisition at 49dB, 55dB and 60dB for exposure times of 1, 10 and 100 seconds respectively.

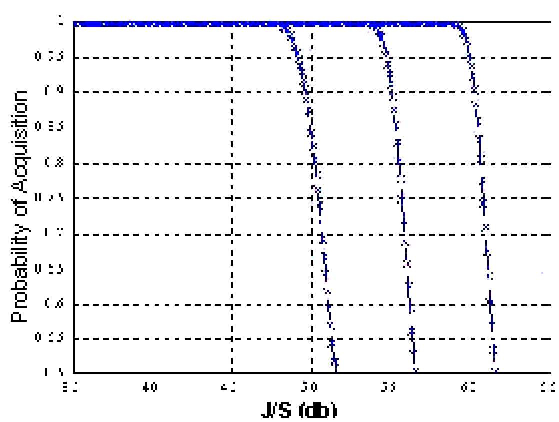

Figure 12 Probability of Acquisition using Direct Y Search and Standard Clock (Exposure times are 100 sec, 10 sec, and 1 sec respectively reading right to left for a particular receiver)

From Figure 13, for the superior clock, the simplified MAGR can achieve a 95% probability of acquisition within 100 seconds at a 37 dB J/S. The GRAM can achieve a 95% probability of acquisition within 10 seconds at a 37.5 dB J/S and within 100 seconds at about 44 dB. For the storage receiver, it could achieve a 95% acquisition at about 49dB, 55dB and 60dB J/S with exposure times of 1, 10, and 100 seconds, respectively. Note that the probability of acquisition of the storage receiver is independent of clock error since all bins will eventually be searched. The mean time of acquisition is clock dependent, but not the probability of acquisition.

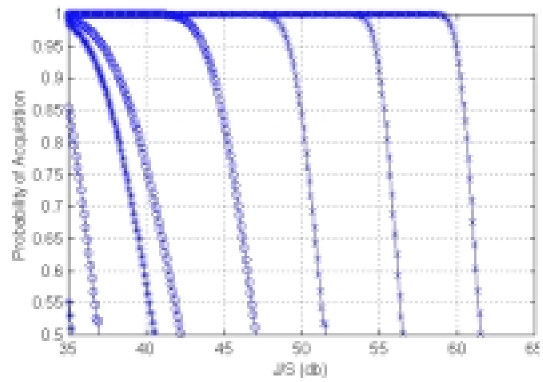

Figure 13 Probability of Acquisition using Direct Y Search and Superior Clock

5 APPLICATIONS OF STORAGE RECEIVERS

In the following sections, some of the applications for the storage receiver are described and the benefits of this approach are discussed.

5.1 Covert GPS Receiver Navigation Capability

In Figure 14 a submarine application for GPS is illustrated that uses a storage receiver to minimize the time needed to be spent on the surface in order to achieve a navigation fix. For stealthy or covert operations, it is important to minimize antenna exposure. Furthermore, a real time fix is often not necessary because a dead reckoning device such as an inertial navigator is adequate to extrapolate the GPS fix to present time. NAVSYS is delivering under contract to SPAWAR a DSR Model 200 (see Table 1) with data playback capability to be used for trials of this application.

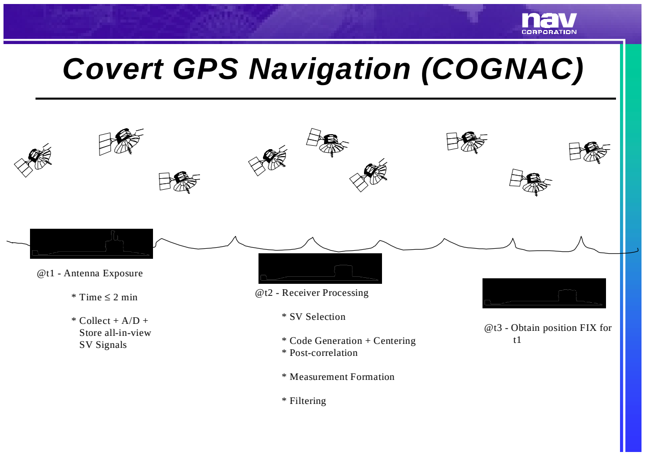

Figure 14 Covert GPS Navigation Application

Figure 15 summarizes the advantages of the storage receiver for the submarine application and other covert applications where the antenna exposure time must be minimized.

Figure 15 Stealthy or Covert User Application of Storage Receiver

5.2 GPS Signal Environment Analysis

The post-test analysis capability of the digital storage receiver enables it to be used to capture segments of the GPS signal environment for detailed analysis. This capability has been used for a variety of different applications by NAVSYS' customers. Some of these are briefly described below.

An older generation version of our NDAQ was used to collect GPS signals from an aircraft flying above the ocean to characterize the specular component of the GPS signal that would be received by sea-skimming missiles. This was post-processed producing the first quantified results of multipath signals in a land and sea environment[7].

The same equipment was also used to collect flight test data that provided measurements on the signal reception characteristic of a GPS pseudolite from an aircraft with a top and bottom mounted GPS antenna[8]. This flight test data was then played back post-test to replay the flight experiment through different configurations of a pseudolite receiver to develop optimized tracking performance in the environment.

The digital recording architecture has also been used for tracking missiles. NAVSYS delivered hardware to the Space Strategic Defense Center (SSDC) which was installed on two Strypee missiles[9]. The digital front-end was connected to a 2 Mbps telemetry link and the data was recorded at the range for post-processing. This digital GPS translator architecture was used to demonstrate the ability to maintain carrier lock under high dynamics using test data collected from these missile launches and from test data collected at the Holloman test track[10].

The DSR Model 100 data sensor was used by the Air Force to collect data on the GPS signals in space in the Falcon Gold experiment. The GPS sensor was installed on a Centaur orbit transfer vehicle and the recorded data telemetered to the ground for analysis[11]. This test data proved the capability to track the GPS satellite signals from LEO to GEO orbits (see Figure 16).

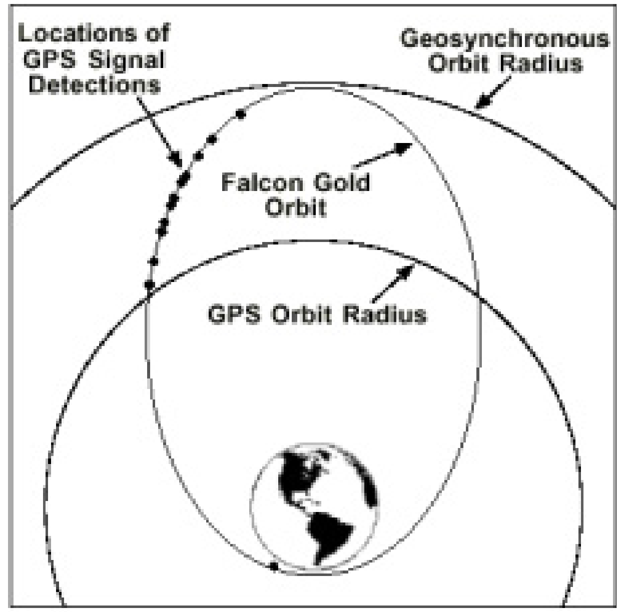

Figure 16 Falcon Gold DSR Test Results

5.3 Precise Positioning Service (PPS) Operation for Expendable Sensors

The DoD is considering using GPS for some disposable applications. This includes tracking radiosondes[12], dropwindsondes[13] and sonobuoys[14]. In these applications, the sensor is not recovered which, to date, has limited their use to SPS GPS receivers. With the concern regard to jamming on the battlefield, the storage GPS receiver approach is being viewed as a solution to this problem. In this application, the GPS sensor data is telemetered to the ground station instead of the navigation solution. The PPS security is therefore maintained in the ground system and only the front-end of the receiver is discarded.

5.4 GPS Satellite Simulator Applications

GPS satellite simulator test facilities are used to checkout the software and hardware of GPS receivers and their augmentation systems. In general, they include satellite signal simulators, differential augmentation simulators, and interface emulators. All testing is run in real time and requires considerable hardware and human assets. Initially the dynamic scenario to be simulated must be designed and stored in the simulator control computer. The dynamic scenario specifies all relevant factors

including the trajectory of the GPS receiver(s), the satellite constellation, the signal power and waveforms, environmental factors including propagation errors, and jammer effects. In general, there is considerable equipment setup and calibrations that must be performed prior to actually exercising the scenario. In addition, the satellite simulator and control equipment are expensive resources typically costing on the order of 1 million dollars.

The data remodulation capability of the digital storage receiver (see Figure 1) can be used to provide a high fidelity signal simulation capability. NAVSYS have developed a Matlab product that allows digital files to be generated for selected scenarios. This provides low level visibility and control of the actual simulated environment (see Figure 17). This simulation tool has been used for example, to develop high fidelity high dynamic carrier phase tracking algorithms.[15]

The digital storage receiver also enables the same scenario to be replayed with different equipment or modified equipment versions. For example, in source selection applications, the scenario may be rerun with many competing vendors' equipment. Furthermore, in source selection applications, it may be desirable, for historical or litigation purposes, to have a permanent record of the scenario that was run.

The advantages of this application can be summarized as follows:

- Enables follow-on tests at different times and locations without most expensive resources and preparation
- Simulates nearly exact repeatable RF conditions as many times as desired
- Saves RF conditions for historical and legal purposes.

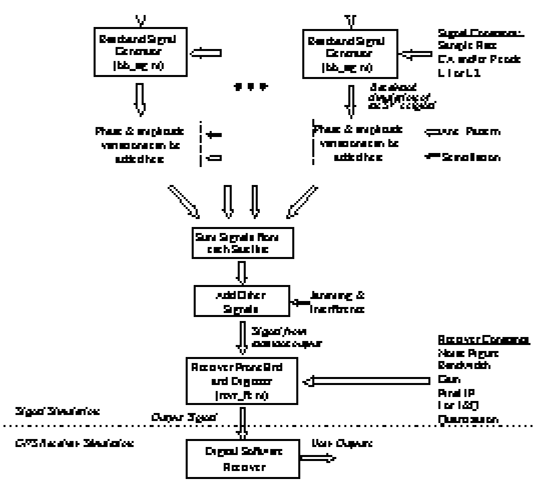

Figure 17 Matlab Signal Simulation Tool

5.5 GPS Jamming Detection and Location

GPS has been adopted for virtually every military mobile operation and will be the primary navigation equipment for all phases of commercial flight. Of critical importance are its accuracy, integrity, availability, and continuity of service in these applications. As a low power radionavigation system, it is susceptible to both intentional and inadvertent interference. The situational awareness of the availability and health of the GPS signal in the operational area of interest is required. If the GPS signal is being jammed, then the nature of the jamming signal, its source and location are of critical importance. This information will be necessary to take corrective action including prosecution of the interfering source.

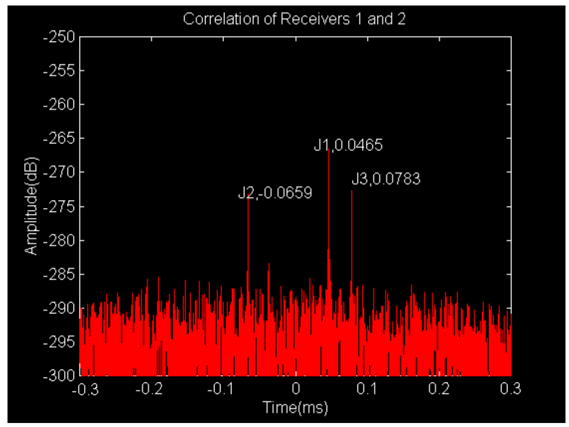

Figure 18 TDOA Jammer Simulated Data Results

In this application, which is described further in another paper being presented at this symposium[16], the GPS receiver with storage capability is used to collect snapshots of the jammed signal spectrum, synchronized with a GPS time mark. When the GPS receiver indicates that interference is present, it transmits this buffered data to a central processing location. The advantage of this capability is that it enables TDOA/FDOA jammer location techniques to be applied which enable location and identification of large numbers of jammers. In Figure 18, an example is shown using simulated data where three jammer signals can be seen in the cross-correlated spectrum. NAVSYS DSR 100 hardware will be used to collect jammer location data in a test planned shortly by AFRL and the AF Space Battlelab[16].

5.6 Mobile Cellular Location System

This application applies to the rapidly burgeoning field of cellular telephones and other personal, portable devices that enables the masses in-situ access to data and voice capabilities. The Federal Communications Commission (FCC) has mandated various phases of mobile location capability be included in future cellular telephones. At this time it is not clear whether the methodology for achieving the navigation capability will be with GPS or be with another capability such as Time Division Time of Arrival (TDOA) capability. The decisive factor on

whether GPS will be the chosen PCS navigation technique will likely be the economics of placing GPS hardware in the cellular type device and the performance that can be achieved using GPS location.

NAVSYS' patented TIDGET™ technology[17] uses the digital storage receiver approach to provide a mobile location solution (LocatorNet™) for PCS applications. There are multiple benefits of the digital storage approach for this application. First, in order to provide a rapid response to emergency calls, the GPS exposure time must be minimized. This is achieved in the LocatorNet™ system architecture by using the storage receiver capability to capture a "snapshot" of the GPS data in a buffer which is then transmitted to a central processing location where he navigation solution is computed. This significantly reduces the time-to-first-fix and has the added benefit if reducing the power and cost of the hand-held PCS device. In Figure 19, one of the PCS devices that is in operation using this technology, the Personal Guardian, is shown[18].

Figure 19 Personal Guardian location device

6 CONCLUSIONS

The rapid improvement in computer throughput has made direct storage and subsequent processing of the wide-band GPS signal a practicality for many applications. In this paper, an analysis was included of the performance advantages in using the digital storage receiver for direct P(Y) code acquisition in a jamming environment. Results were shown that compared the performance of a conventional sequential search GPS receiver with a storage type receiver. The results indicate that the storage receiver has the potential for significant improved probability of acquisition for a fixed antenna exposure interval. Alternatively, the storage receiver can reduce the average time of antenna exposure for a given probability of detection. These advantages accrue from the storage receiver's ability to "re-circulate" the stored data to the available correlator resources.

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